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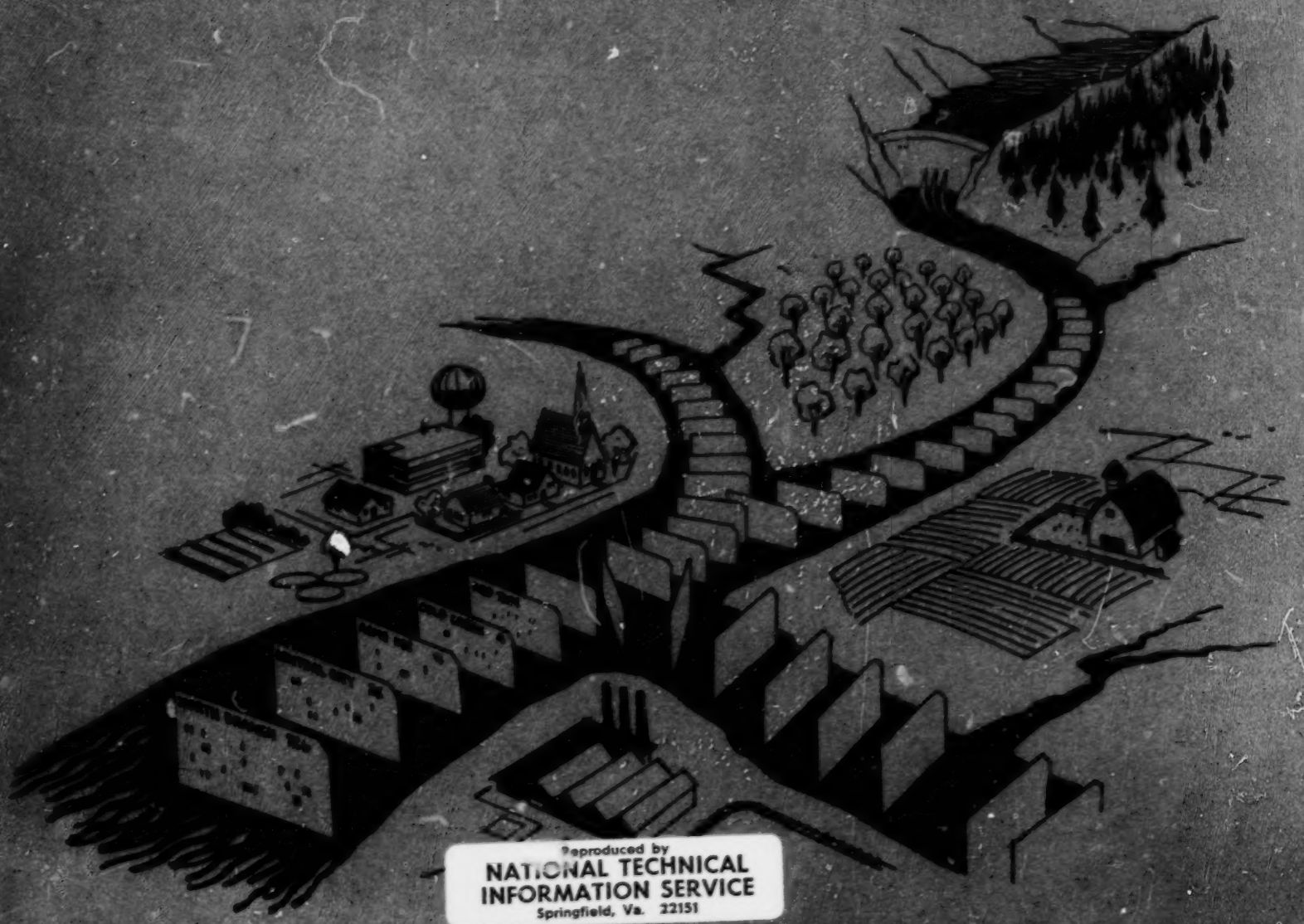
The Economics of Water Supply and Quality



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ENVIRONMENTAL PROTECTION AGENCY • WATER QUALITY OFFICE

February 1971

The Economics of Water Supply and Quality

by the

Harvard Water Program
Harvard University
Cambridge, Massachusetts

for the

WATER QUALITY OFFICE
ENVIRONMENTAL PROTECTION AGENCY

Project 16110 DTF
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ABSTRACT

Research has been directed to a series of problems in water resource management. One pair of projects has focused on problems of water supply planning under uncertainty, and improved methods of analysis for planning have been developed.

A set of four research efforts has been devoted to problems of water quality management, with special attention given to the decisions faced by municipalities and regional authorities. New conceptual models of quality management institutions have been proposed, and the conceptual framework has been applied to several sample river basins.

A third focus has been on the development of improved computing methods for analysis of river basins. Two projects have contributed new analytical models for preliminary screening of river basin designs. Special attention has been directed to the analysis of flow augmentation for water quality management.

Finally, research has been carried out on the use of regional analysis in water resource planning. A static regional input-output model has also been developed that can analyze the interrelations between regional growth and efforts at water quality control.

As a subsidiary result of this grant research, a monograph on water quality management has been prepared. It includes much of the material described above, as well as five additional essays.

This report is submitted in fulfillment of Grant Nos. WP-00919 and 16110 DTF from the Water Quality Office, Environmental Protection Agency.

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SECTION I

INTRODUCTION

This report covers four years' research by members of the Harvard Water Program.[1] The greater part of the financial assistance for this work on "The Economics of Water Supply and Quality," was provided originally by the U. S. Public Health Service[2] (Grant No. WP-00919). The grant was for a three-year period, January 1966 through December 1968. The terms and level of financing remained unchanged when, in 1966, the grant program in water quality was transferred from the U. S. Public Health Service to the Federal Water Quality Administration of the U. S. Department of the Interior. This report summarizes work performed during the initial period, and includes research supported by a nine-month extension that began in January 1969 (Grant No. 16090 DTF).

Section II of this report presents a summary of the work carried out by the different participants in the program.[3]

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[1]Although the research described was supervised by Robert Dorfman, Harold A. Thomas, Jr., and Henry D. Jacoby, a major portion of the work was carried out by undergraduate students, graduate students, and visiting scholars.

[2]Financial support was also contributed by Resources for the Future, Inc., Washington, D. C.

[3]The full reports of research results are contained in a set of Harvard Water Program Discussion Papers, various working documents, and a number of published articles and books.

It is organized according to the four principal areas of research outlined in the original grant proposal:

--the economics of water supply,
--the economics of water quality,
--computing techniques for basin-wide planning, and
--the use of regional analysis in water resources planning.

In addition to research in these four areas, a subsidiary purpose of Grant No. 16090 DTF was to facilitate the preparation of a monograph on water quality management. The monograph is titled Models for Managing Regional Water Quality. Six chapters of the completed monograph are the direct result of research financed by Grant Nos. WP-00919 and 16090 DTF. Another two chapters are the result of investigation done under grants from the FWQA to researchers at Harvard University for work on "Operations Research in Water Quality Management" (Grant No. WP-00111) and "Dynamic Planning Techniques for Pollution Abatement" (Grant No. 16090 DSS).

SECTION II

RESEARCH EFFORTS UNDERTAKEN

Research on the Economics of Water Supply

Many of the water-related problems of public policy involve systems subject to uncertainty in supply--e.g., municipal water systems subject to uncertainty in climate and in consumer demand, or water quality systems which are influenced not only by fluctuation in river flow and temperature but by variation in pollution loads. All planning models must deal with this uncertainty in one fashion or another, and in our work we have been particularly concerned with the economic benefit and loss functions that are used to represent the economic impact of variation in water supply and quality.

Two of our research efforts were devoted to aspects of planning under uncertainty. Both were oriented primarily toward problems of water supply: one (introduced first below) drew on the experience of water systems in deficit in order to study the economic losses associated with water shortage and to analyze potential improvements in water supply planning practice; the other was primarily theoretical in nature and explored the expected responses of different types of economic units to uncertainty in supply.

Municipal Water System Planning

The Problem of Drought and Water Supply Shortage

During the early months of the grant period, our interest in the economics of water supply and the problems of system planning was heightened by the fact that the northeastern United States was passing through what later turned out to be the most serious period of a prolonged and severe drought. Many municipal water systems experienced shortage during this period, and the event provided a rare opportunity for

research on the economic loss associated with water supply restrictions. That so many systems experienced difficulty also raised a question about the nature and adequacy of the planning procedures used in the design of municipal water supplies. Research on this problem was carried out by Clifford S. Russell, and the results are reported in The Recent Northeast Drought: Short-run Costs of Water Shortage and Lessons for Water System Planning [15].[4]

The Russell study contributes insight into the link between system adequacy, climatic variation and the levels of shortage experienced. And this insight, in turn, leads to a method for making probability statements about various levels of shortage for given system adequacy levels. The study also produces evidence on the economic impact of water shortage, which makes it possible to translate shortage figures into costs that can be compared with the costs of system improvements. These results lead to the formulation of a revised method for water system planning.

The framework within which the model is presented is that of a capacity expansion model in which the costs of meeting a growing demand are balanced against the losses incurred by not doing so. Attention is concentrated on additions to system size (as measured by the amount of water available at a given level of assurance) as the relevant method of improving system adequacy. The alternative possibility of altering system demand or of making more efficient use of the water available from a given system (as, for example, with leak-control programs) is outside the scope of the study. In addition, it is assumed that the historically given price structure is to be continued indefinitely into the future. All alternative plans for the growth of the system are assumed to share the aim of meeting the level of demand implied by that given price structure.

In order to discuss the model and the drought study findings, it is necessary to introduce a few key definitions.

(i) System Capacity (or Safe Yield) is that constant rate of withdrawal from a surface water system which is assured at some chosen probability level (e.g., that constant withdrawal rate which can be maintained 95 percent of the time or in a repetition of the "five percent drought").

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[4] In this effort, we were fortunate to have the collaboration of Professor Robert Kates and Dr. David Arey of Clark University who also were involved in a study of the impact of the drought under the sponsorship of Resources for the Future, Inc. The results of our two research efforts have now been combined into a book by Russell, Arey, and Kates, Drought and Water Supply: Implications of the Massachusetts Experience for Municipal Planning [16].

(ii) System Demand is the level of demand for withdrawals from the system which exists under the particular conditions (e.g., price, weather) being discussed. Total demand may usefully be thought of as the product of the level of per capita demand and the size of the population, and demand may be projected into the future for planning purposes using separate projections of these variables.

(iii) System Adequacy is indicated by an index developed in the course of the study: it is equal to the ratio of (projected) demand to safe yield. The larger this index number, the lower the level of relative system adequacy.

(iv) Shortage is defined as the percentage difference between the existing level of demand and the actual deliveries (or amount of water available for delivery, in the future).

(v) Climatic Variation is relevant both to the level of demand and of supply. Most attention, however, is focused on the effect of climate on the availability of water. The principal source of information on climatic variation is rainfall data.

Development of a Model for Water System Planning

The construction of a model for the planning of system capacity expansion involves three major questions. First it is necessary to know in quantitative terms how the level of system adequacy and the severity of climatic events interact to create water shortages. This question is at the heart of the attempt to attach probabilities to shortage levels. A second question concerns the size of the economic losses associated with various levels of shortage. An answer to this question is necessary in order to translate the analysis of the physical world into economically meaningful terms. The third question, central to the model building effort, is that of the costs of improving system adequacy. Because the study concentrates on additions to system capacity as the means of improving adequacy, the third question is restated to involve the cost of adding to capacity--i.e., of adding safe yield.

As for the first question, the study begins by hypothesizing a model in which the level of shortage (for a given adequacy level) depends on the fraction of safe yield flow available, and where this in turn is determined by the extent to which current natural inflow of water differs from the flow associated with safe yield. The climatic variable used in measuring the severity of events is the four-year cumulation of annual rainfall amounts. This series is chosen in preference to one of streamflow or watershed yield primarily on practical grounds of data availability. Investigation, however, confirms that the series is fairly closely related to streamflows.

The second question mentioned above, that of the size of the economic losses caused by varying levels of shortage, is examined using extensive data collected in three Massachusetts towns at the end of the 1961-65 drought. These data consist primarily of interview results from contacts made with local firms in the commercial and industrial sectors. These are supplemented by interviews with certain municipal officials, by newspaper searches and by the use of published results concerning household demand functions for water.

Regarding the third question, two independent approaches are used in estimating the costs of adding to safe yield. First, on the basis of published data a "theoretical" cost function is estimated. This involves estimating the cost of building a reservoir of specified volume and then calculating the storage volume needed on streams of various sizes to provide a given firm withdrawal rate with (approximately) a five-percent failure rate. The second estimation method involves the use of historical cost estimates from engineering reports submitted over the years to five Massachusetts cities by consulting engineers.

These three aspects are then combined into a planning model for municipal supply system for which demand is growing over time. At any particular time demand bears some particular relation to safe yield, and this implies some expected loss (considered as a best estimate of the loss to be incurred during the period). System adequacy may be changed one or more times during a planning period by making additions to safe yield. The task of the planning model is to determine the optimal sizes of the increments to system capacity and the optimal times to build them over a sixty-year planning horizon. The resulting model is a nonlinear programming problem with linear constraints, and its solution is approached by the "method of feasible directions."

From the solutions to this model, it proves possible to extract information on the optimal size and timing of capacity additions for any municipal system. And thus this particular aspect of our research has led to resu_ts that may be of immediate and practical usefulness to water system planners --both in the design of independent municipal supplies and in the development of economic data for systems analysis of larger, interdependent, basin-wide planning problems.

Theoretical Models of Response to Uncertainty

Because the response of water users to variation in supply --and instream quality--is such an important aspect of the economics of water system planning, it was decided to seek an improved theoretical basis for our work in this area.

To this end we took on a study of the behavior of consumers, business firms, and public decision bodies under uncertainty. The results of this work, most of which was carried out by Stephen J. Turnovsky, are reported in a series of working papers and articles, and in two chapters in the new monograph on water quality management.

A Model of the Response of Consumers to Uncertainty in Supply

The main portion of the study focuses on the response of the individual consumer to situations where the price of a particular good may be fixed but the quantity actually available to the consumer is uncertain; furthermore, attention is concentrated on the case where the consumer lacks facilities for storing the good in question. Uncertainty in water supply from a stochastic stream or from a badly managed municipal water system are obvious examples of this type of situation. The administrative procedures for setting water rates usually do not allow prices to respond to variation in supply, and some other rationing device is necessary to allocate the available supply among users. As a result, the uncertainty in climate or in system performance is transformed into an uncertain supply to the customer.

The initial efforts are directed to the individual consumer, and the analysis is based on the assumption that the producers will attempt to provide whatever the consumers plan to purchase, although the actual supply can only be guaranteed within some random error of the planned consumption. The theoretical model of the consumer's response in this situation involves the extension of the classical utility framework to encompass stochastic supplies, and an attempt is made to predict how consumption plans would respond to changes in the variance of the supply distributions using this model.

The results of this work are reported in a paper entitled "A Model of Consumer Behavior Under Conditions of Uncertainty in Supply" [19]. One of the more interesting conclusions is that, if x_i^* is the planned consumption of commodity i and σ_i^2 is the supply variance of commodity i, then

$$\frac{\partial x_i^*}{\partial \sigma_i^2} > 0 \quad .$$

As uncertainty (as measured by supply variance) increases, consumers plan to purchase <u>more</u> of the commodity. This result follows essentially because of diminishing marginal utility considerations which imply that the loss associated with being short of a particular commodity exceeds the gain

associated with an over-supply. In other words, under uncertainty the consumer increases his margin of safety and orders more than he would if he were certain of receiving the desired amount. In addition, the model indicates that a consumer who has already experienced uncertainty in the past will react less positively to increases in σ_i^2 than a consumer experiencing uncertainty for the first time.

An Empirical Test of the Theory

In order to test these theoretical results, the model is applied to data from the water supply systems of nineteen Massachusetts towns over the 1961-65 drought period. Demand functions for water are estimated using a combination of cross-section and time series analysis and drawing on data made available by the work of Clifford S. Russell discussed above [15]. Both the phenomena predicted by the theoretical model are found to exist in this particular case: σ_i^2 proves to be a significant explanatory variable in the estimated demand equations, but less important when the consumer has been subjected to uncertainty in the recent past. This research is described in detail in "The Demand for Water: Some Empirical Evidence on Consumers' Response to a Commodity Uncertain in Supply" [24].

Extension of the Model to Consider the Behavior of the Firm Facing Uncertain Factor Supplies

The same theoretical apparatus which is applied to the consumer is also turned to the problem of the firm with uncertainty in factor supplies. The firm studied is assumed to produce a single output and to trade in competitive input and product markets. But as opposed to the conventional analysis of the competitive firm, the quantities of input factors available are assumed to be uncertain. Once again prices are assumed fixed. The firm is assumed to decide what inputs it plans to use and to convey these plans to the suppliers of raw materials (e.g., water) and other inputs. The suppliers of inputs then undertake to provide the desired amounts, but due to hydrologic uncertainty are only able to guarantee their supplies within some random error, so that the quantities actually delivered to the firm are in general different from those which it anticipates.

The behavior of the competitive firm under these circumstances is explored in a paper on " The Theory of Production Under Conditions of Stochastic Input Supply" [23]. A similar case where the firm can buy any quantity it desires of the input factor but where the input price is uncertain, is analyzed in

a paper on "The Behavior of a Competitive Firm with Uncertainty in Factor Markets" [20]. Still another application of this same model is the case where the firm is faced with uncertainty in demand for its product. In "Stochastic Demand and the Theory of the Firm" [21] an attempt is made to delve beneath the firm's revenue and cost functions and to analyze how decisions concerning the use of inputs in the production process are affected by the uncertainty in demand for the final product.

Government Investment Under Uncertainty

In "Some Criteria for the Optimal Selection of Risky Investment Projects" [22] the models developed in the preceding papers are applied to the general problem of investment under uncertainty: attention is focused on the problem of optimal government investment in projects whose outputs --which are services or commodities consumed by the population --are uncertain. As before, the example used is water: because of uncertainty caused by natural phenomena, the government supplier cannot guarantee 100 percent reliability and can only undertake to satisfy consumers' demand with some prescribed probability. The parameters that describe the probability distribution of supply experienced by the consumers reflect, at least in part, the design of the water system, and to that extent they are within the government's control. For the purpose of this analysis, it is assumed that these parameters are completely within the government's control, and that by increasing expenditure an improved systems can be provided. Accordingly, once it has been established how consumers may be expected to respond to--and are affected by--uncertain supply, the next step is to determine the socially optimal design.

Many of these research results were drawn together into two essays focused specifically on the problem of uncertainty as it affects the design and operating decisions made by public agencies [25, 26].

Research on the Economics of Water Quality

Our work on the economics of water quality has placed heavy emphasis on the interaction of economic, technical, and political factors in water quality management problems. Particular attention has been devoted to the regional quality management authority as a key agent in many quality management efforts, and to the municipal entities which they must regulate. Our research also has touched on special problems of estuarine quality management.

Influence of Technical, Economic, and Political Factors on Quality Management Efforts

One of the central research efforts, conducted by Robert Dorfman and Henry D. Jacoby, has been directed to the study of political and economic considerations as they impinge on technical and engineering solutions of water quality problems. This work emphasizes that what ought to be done is never clear, and is a matter of judgment, about which opinions differ legitimately. What will be done about water quality in any context is therefore a reconciliation of diverging opinions and conflicting interests. This obvious fact would not be worth mentioning but for two circumstances. First, this conflict is almost universally ignored (or at least concealed) in most discussions of water resource design and project evaluation. Second, as a consequence of the first, there are no known methods of design that take political considerations into account.

The Task of River Basin Authorities

In the attempt to study the institutional and political side of water quality management, attention has been focused on the most promising legal expedient for dealing with quality problems--the River Basin Authority. A River Basin Authority is a special governmental institution empowered to regulate the use of a segment of a river, or in some cases an entire river. The powers to be conferred on River Basin Authorities to enable them to discharge their functions are still obscure.

At the very least, a River Basin Authority is usually responsible for prescribing levels of waste treatment for individual dischargers or setting limits on the quantities of pollutants that may be discharged. It also may be authorized to levy various taxes and charges to finance its operations and to induce water users to behave in ways that make efficient use of available assimilative capacity. In some cases, an Authority may be empowered to finance and operate treatment plants, waste diversions and collection facilities, reservoirs, and so on. Indeed, one of the purposes for studying River Basin Authorities at this time, when so few are in operation, is to clarify the proper role that each of these powers and authorities must play.

The River Basin Authority has a formidable task. In order to perform its function it has to alter the established and convenient practices of influential social units such as industrial firms, cities, and even state governments, and to encroach upon their former prerogatives. Its responsibilities are defined in terms of a range of activities that overlaps

and conflicts with the jurisdiction of older, established governmental units. In such circumstances, the effectiveness of the Authority in imposing and implementing its standards will depend at least as much upon its ability to persuade as upon its power to compel. The approach of this research, therefore, has not been to analyze this governmental unit as if it were in a position to set forth objectives and ordain performance. Rather an attempt has been made to analyze the Authority in the light of its problems of gaining adherence to its goals and acquiescence to its regulations and charges.

A Conceptual Model of a River Basin Authority

The outcome of this investigation has been a new conceptual model of the functioning of River Basin Authorities. The model can utilize data and subjective judgments about technological, economic, and political conditions in a river basin and can give indications of the type of quality management plans that are likely to be adopted in the circumstances. It is, therefore, a predictive theory of the performance of this type of social institution.

The key concept underlying the model is that of the "Pareto-admissible" pollution abatement plan. The primary role of the River Basin Authority is seen as that of arbitrator --balancing the partially conflicting desires of the industries, municipalities, conservation groups, governmental agencies, and other interests that make up its widely varied constituency. The Authority operates under a number of technical, economic, and political constraints, and within these limits it must find a solution that is attractive to some if not most of the interested parties, and one that is not absolutely unacceptable to any of them.

Since the Authority is sensitive to its constituents' interests, it is safe to assume that it will be only by inadvertance that an opportunity to aid any one interested group will be passed up, provided no others object. Those decisions, or quality management plans, that offer no opportunity to further aid any one group except at the expense of others, are termed "Pareto admissible." If, as Dorfman and Jacoby argue, it may be presumed that the River Basin Authority's choice will be restricted to the subset of Pareto-admissible pollution abatement plans, then the range of likely choice is drastically reduced. Where in the range of permissible choice the ultimate decision will fall depends on the relative influence of the contending parties within the decision process of the Authority.

Dorfman and Jacoby have shown how to construct a mathematical problem whose solution will be one of the Pareto-admissible decisions available to an Authority. They identify each of

the relevant interest groups, i, that may be concerned with the choice among alternative quality management plans, X. Depending on the decision taken, each group realizes some level of net benefits, $NB^i(X)$. The mathematical problem is constructed by assigning political weights, w_i, to the various groups concerned and then finding the decision that maximizes the weighted sum of net benefits, denoted by $\Sigma w_i NB^i(X)$, while satisfying constraints and relationships that describe the technological connection between abatement measures undertaken and quality achieved, between abatement level and cost incurred, and so on.

The range of admissible choice may be traced out by assuming many divergent sets of relative political weights, w_i. The ultimate outcome, naturally, depends on the influence actually exercised in the circumstances--and it is not possible to predict exactly what these relative weights may be. It is possible, however, to apply knowledge of the political facts of life and judge some of the weight allocations as more likely to be experienced than others. And based on these estimates, one may make similar judgments regarding the decisions they call for.

It is, perhaps, unnecessary to argue that a predictive theory, such as the one proposed as a result of this research, may have practical as well as scientific utility. The decisions of any governmental body are predicated in part on expectations about the way in which other governmental bodies will respond to them, just as the actions of the Federal Water Quality Administration are conditioned by the expected response of state and local water quality control agencies. A theory that improves predictive ability can therefore improve governmental decisions.

Besides, at the present time legislation for the establishment of local water quality control authorities is in the process of being drafted and tested. A predictive theory will indicate, among other things, how various provisions of enabling legislation and charters are likely to influence the performance of local authorities. By so doing the theory can assist in resolving some of the still moot questions about the proper conditions and powers to confer upon quality control agencies.

A Preliminary Test of the Conceptual Model

In order to subject the conceptual model to a preliminary test, it has been applied to a hypothetical river basin. The analysis makes use of realistic technical and economic data; the basin itself has been kept simple in order to facilitate this preliminary application. Several municipal and industrial

dischargers contribute to the generally poor quality of the sample river; most of these same agents, along with others both in and outside the basin, have an interest in bringing the river to a higher quality standard. The question, naturally, is how high a standard to strive for and how to achieve it. The model focuses on a river basin pollution control commission charged with formulating and implementing a regional plan, and the analysis considers the way economic and technical factors combine with political considerations to influence commission decisions.[5]

Municipal Waste Management

In an attempt to cover some of the key aspects of the economics of water quality, special attention has been devoted to the municipality as a participant in the overall management process. Most community water treatment facilities are organized under the municipal governmental structure, and the success of the Federal pollution control program depends in large measure on the response of municipal authorities to national policies.

Difficulties Faced by Municipal Wastewater Managers

Of course, municipalities handle not only domestic sewage but also the wastes of certain industries within their municipal sewer service areas. For example, under current water pollution legislation, large Federal and state grants are available to ease the burden of the construction cost of municipal waste treatment facilities, but no cost sharing or incentive schemes of any magnitude have been agreed upon to aid industries who are managing their own wastes. There is, therefore, a strong incentive for industries not previously served by municipal systems to seek such a connection. This presents the municipal water manager with the problem of allocating the financial burden among industrial firms, both those already connected to the sewer system and those joining in, and between business

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[5]This experimental application, along with a summary of the conceptual model, has been published in an article by Robert Dorfman and Henry D. Jacoby entitled "A Model of Public Decisions Illustrated by a Water Pollution Policy Problem." The paper appeared first in a Congressional Joint Committee Print [4], and subsequently a revised version has been published in an edited volume on public expenditure and policy analysis [5].

firms and domestic waste sources. The mix of policy instruments used by the municipal water and waste disposal system manager to deal with these divergent interests influences the effectiveness of the Federal program. In order to explore this question, we have undertaken a study of what actually happens when quality management decisions are faced by a municipality serving large industrial polluters.

A Case Study of Municipal Wastewater Planning

Once again, as in the case of the studies of municipal water systems under shortage, we were fortunate to encounter two New England municipalities--Nashua, New Hampshire and Fitchburg, Massachusetts--that serve as excellent case examples. The two are in the same river basin: Fitchburg is the major upstream polluter of the Nashua River before it reaches the town of Nashua, and both these cities contribute to the poor quality of the Nashua as it merges with the Merrimac River. Both are small municipalities with substantial industrial sectors and both contain industries (tanning and paper) which are heavy polluters. In addition, both towns have been in the midst of planning new treatment facilities and in negotiating the town response to recent Federal water pollution legislation.

The report by Don Howarth on "The Federal Water Pollution Control Program: A Case Study of Two New England Towns" [6] presents the results of our study of the impact of the pollution control program on these municipalities. There are several major issues to which this study is addressed. The first concerns the alternative fiscal instruments available to a municipality for financing treatment cost. The two basic schemes which are available to municipalities are user charges and property taxes on assessed evaluation. It is true that if a charge system is chosen, it can be constructed in many different ways. It appears in our studies, however, that the critical municipal decision is whether or not to use user charges at all; and an attempt is made to build a model of this decision in order to analyze the influences which affect it.

The Howarth report examines the issue of property taxes versus user charges in terms of both efficiency and equity; moreover, the report discusses the degree and direction of income distribution under each scheme, and it is argued that a charge system is preferred on this score. In addition, it argues that economic efficiency can only be achieved through the establishment of the user charge alternative. The report goes on to show, however, that when the choice between the two financing schemes is left in the hands of local decision units, there are circumstances under which the municipality can be expected to choose the property tax alternative.

In order to pursue the impact of different financing arrangements on the municipality, the report examines the question of whether the choice of financial instruments would be expected to have an effect on the municipality's bond market position, and vice versa. Finally, the report recommends changes in the Federal water pollution control legislation which would guide municipalities toward improved management policies from both an efficiency and an equity standpoint. Specifically, the report argues that some form of user charge scheme should be made a prerequisite for Federal support of municipal treatment plant construction.

Municipal Evaluation of Alternative Quality Management Plans

A study by Clifford S. Russell provides a closer inspection of the empirical problems of implementing the conceptual model proposed by Dorfman and Jacoby. The attitudes of municipal authorities are an important influence on the measures taken by River Basin Authorities. As a result, the prediction of likely basin-wide quality decisions requires an estimate of the value of alternative plans--the $NB^i(X)$ term introduced above--as viewed from the standpoint of participating cities.

The Viewpoint of Municipal Decisionmakers

In the planning of regional quality control, major municipalities will generally be represented by their elected officials, who will be called upon to evaluate alternative basin schemes, and who probably will have the power to commit their respective cities to future changes in waste management. In carrying out their responsibilities these officials will, of course, be interested in the balance of costs and benefits for their constituents that each of the alternative proposals implies. A prime consideration in any negotiations on a basin plan, therefore, will be the cost of new municipal waste collection and treatment facilities and the distribution of these costs among the city's residents. On the other side of the balance will be a number of advantages: increased recreational opportunities (at the city's waterfront or elsewhere), an improved aesthetic situation in the vicinity of the riverbank or elsewhere, and higher quality water at the intakes of the municipal water supply system or of local self-supplied industries. Judgments about these costs and benefits, and their distribution, will determine whether a city will support or oppose any particular abatement plan.

Three questions form the basis of Russell's study of this phenomenon: (1) what are the categories of benefits and costs that deserve to be considered, (2) what are the methods by

which the magnitudes of these effects may be estimated, and (3) what is the process by which we may visualize these considerations being combined to form the overall judgment of the "value" to the city of a particular abatement plan?

A Model of Municipal Decision Processes

The results of the research that follows from these questions are reported in a paper that forms one of the chapters in the new water pollution monograph. Russell first develops a descriptive model of the process by which municipal decision-makers balance the costs and benefits that a particular scheme implies for different groups of constituents. The model shows how municipal officials may be imagined to go about integrating these data to form their decisions to support or oppose particular basin-wide plans.

The Russell approach to the functioning of governmental institutions is an extension of that proposed and tested in the work of Dorfman and Jacoby. The government is viewed as having as one of its chief preoccupations the maintenance of some level of support among the set of local interest groups; it is very important to a city administration how the costs and benefits are distributed among these groups. Part of the problem, of course, is that different groups carry different "weights" in the minds of political leaders; some will be more politically influential, some more "deserving" on one basis or another. Together the influence and deservingness of a group will determine the relative amount of attention that the leadership feels must be accorded it in assessing the overall impact of a particular program.

Once again interest groups are defined--only now the interests are internal to the city. Individual groups may be indicated by the index j. The gross quality benefits a group realizes from a particular abatement plan X are determined by the quality improvement q_X that the plan yields. Russell defines the marginal benefit to group j as $\psi_j(q_X)$.

If the total annual costs of compliance with the plan that would bring quality change q_X are C, and the share of group j, under a particular financing scheme is γ_j, then the annual net benefits of the plan to the group are:

$$\int_0^{q_X} \psi_j(q_X)dq_X - \gamma_j C \equiv NB^i$$

Next, Russell assumes that political support for the city administration on the part of a group will be positively related to the size of the group's net benefits resulting from the river quality change and accompanying costs. Further, the city administration may be viewed as having as one of its principal, if not its overriding, goals the maintenance of support among its constituents. Since there will be, at any one time, only a relatively small number of key issues on which decisions must be made (and on the basis of which political support can be gained or lost), and since the significant interest groups will be known to politicians, probably no great violence is done to reality by assuming that these city officials act in making the decisions as though they perceived some (possibly weighted) set of lower limits to the levels of net benefits which may be allowed to accrue to each of the groups. Such a set of constraints may be written formally as $NB^j \geq b_j$

Two possible sources for these values b_j are considered. One alternative is that these values are determined by the local political decisionmakers themselves. If this is the case, we may argue that the set of b_j already reflects the relative political importance of the several groups. If, on the other hand, the b_j represent legal constraints resulting from previous local legislation or from legislation at the state or Federal level, then the question of reflecting local political weights is still open. For example, if group k is a public utility, and if state legislation requires that public utilities be permitted to earn a certain "fair return on invested capital," b_k would be selected so that when $NB^k = b_k$, the utility's profit rate would be at the minimum permissible level. But if the utility is politically powerful, it is likely that the local decisionmakers would feel under pressure to devise plans for which the utility's actual net benefit was larger than this implied legal minimum (or its loss less than the legal maximum). In this situation one might simply imagine that the local authorities choose a new set of b_j such that all outside constraints are at least satisfied and that the more powerful local groups are, in fact, assured of results superior to the minimum levels required by law. Or one might use a model employing weighted net benefits, as does the basin-wide model described earlier. Russell explores all these approaches.

The Importance of Cost-Sharing Schemes Within the Municipality

For a given q_x and cost-sharing scheme, therefore, there will be a value of C that is the largest cost that can be shared without violating a perceived political constraint.

(This value may be zero.) Of course, manipulation of the vector γ_j may permit a higher cost which is "sharable" within the constraint set. Thus, for a given q_X and a particular form of the constraint set, changing γ_j in such a way as to redistribute the cost burden toward those groups enjoying large benefits from q_X will tend to increase the level of C at which the constraint becomes binding.

There will, in general, be fundamental institutional constraints on the vector γ_j; for example, cities may be constitutionally unable to introduce sales or income taxes, to change water rates or to charge for liquid waste treatment on a volume and waste concentration basis. Available tax and charge options may only allow the variation of γ_j over a small region of the relevant space.

In these terms, then, the city's willingness to pay for a given quality change may be defined as the highest level of cost, C, which can be accepted by the city government in complying with that basin plan, subject to the institutional constraints on the variation of the γ_j's and to the political constraints on the resulting net benefits accruing to the interest groups.

A Sample Application of the Model

This conceptual model, and the empirical data developed, have been subjected to a test application. The interest groups that were identified include the domestic sector, tourism-based industries, heavy polluting industries, and commercial and industrial establishments not otherwise classified. The "worth" to these groups of quality improvement includes benefits from

- --aesthetic betterment and increased recreational opportunities related to the river,
- --lower water supply treatment costs due to improved upstream treatment of oxygen-demanding wastes, or
- --lower water supply treatment costs due to lower levels of dissolved solids in the stream.

The sample case is built on the earlier work by Howarth [6] and involves the city of Nashua, New Hampshire.

Estuarine Water Quality Management

During the period from 1961 to 1967 an extensive survey and analysis of pollution in the Delaware Estuary was conducted by the Delaware Estuary Comprehensive Study (DECS) of the Federal Water Quality Administration. Since we are using the Delaware River Basin and Estuary as a laboratory example in much of our research, we have been fortunate to have the close cooperation of the members of the Delaware Estuary Comprehensive Study group as well as of Dr. Robert V. Thomann who directed the original work. Many of the data in our studies were provided by the DECS team.

As we began our work on the economics of water quality, it was necessary for us to pull together the existing information on the Delaware Estuary conditions and to gain familiarity with the systems analysis models which had already been developed for that situation. The study by Grant W. Schaumburg, Jr., "Water Pollution Control in the Delaware Estuary" [17], was our initial effort to develop this capacity and to extend the analysis and add our own contribution to it.

The Schaumburg study uses linear programming models of estuarine pollution abatement to analyze the economic characteristics of different quality management policies. Among the different policy measures considered are the following.

(1) "Required treatment" schemes whereby polluters are required to subject all wastes to a standard treatment process before discharging them into the watercourse.

(2) "Effluent standard" measures whereby the regulatory body specifies how much waste can be discharged by each polluter or by how much each polluter must cut back his waste contribution.

(3) "Effluent charges" whereby polluters are taxed according to the quantity of pollutant discharged.

In addition, the study considers the use of a variety of zoning procedures in combination with these different control measures. Zoning consists of dividing the river or estuary into several different sections or zones according to the type of economic activities which will be allowed or the kind of treatment facilities which must be provided. Zoning is designed to encourage a degree of specialization in stream use and is an aid in seeking abatement solutions that do not require heavy expenditure by polluters who are only making a marginal contribution to the zones of maximum degradation.

The Schaumburg paper presents a clear exposition of the linear difference equation model of estuary dynamics, which is the basis of much current work on estuarine quality improvement. It also provides a clear and concise development of the linear programming models used to analyze the technical and economic characteristics of the various policy measures discussed above, and it applies these techniques to an analysis of the Delaware Estuary

Research on Computing Techniques for Basin-wide Planning

Interaction of Screening Models and Basin Simulation

One of the key aspects of our research over the grant period has been an effort to develop improved systems analysis models for basin-wide planning of water resources. This work has been based on the use of digital simulation techniques. The simulation model with which we have been working is the product of an earlier phase of the Harvard Water Program research, and it encompasses the Delaware River Basin above Trenton, New Jersey along with the Schuylkill River upstream from Philadelphia, Pennsylvania. In its current version, the model allows consideration of thirty-five existing and potential reservoir sites and takes account of water use for recreation, municipal and industrial water supply, electric power generation, flood control and the maintenance of instream flow for quality control.

The model is designed to permit analysis of the interactions among water uses in all the sub-basins of the overall Delaware system. In studying the economics of water supply and quality, it is necessary to consider the Delaware River Basin as a whole, because, for instance, the need to supply water to the city of New York from the upper part of the Basin may conflict with the need to supply water to combat saline pollution in the Delaware Estuary downstream. A simulation model of such a large multipurpose, multi-unit system, however, is necessarily large and complex, and considerable effort has been devoted to the maintenance and improvement of this particular computer program.

The Need for Preliminary Screening Techniques

In our work with this model, we have encountered several difficulties which have led us to shift the emphasis of our research on computation methods for use in planning water systems. There are two major problems that arise in the application of large river basin simulation models: one is the selection of physical designs from the many possible configurations of system components, and the other is the formulation and "tuning" of a reservoir operating policy for the

particular system under study. In an attempt to alleviate these two problems, we have turned our attention to the use of mathematical programming models for preliminary screening of system designs and for an initial formulation of system operating rules.

In order to emphasize the potential usefulness of an effective preliminary screening model, it is helpful to review briefly the way basin simulations are applied in practice. The analyst must select a set of physical plans or "designs" for study, where each design consists of a set of reservoir sizes, construction schedules and target outputs for different water services. Then, using a predetermined reservoir release policy, the model is used to simulate the operation of the system over some period of years and to compute indicators of the economic and physical characteristics of system performance. Even in a system with only three or four potential reservoirs, the number of potential designs is very large, and considerable engineering judgment usually goes into the selection of plans for detailed analysis by simulation.

In some studies, statistical sampling techniques have been used in the selection of alternative river basin plans. In an earlier version of our Delaware simulation model, which was applied to the Lehigh River (a sub-basin of the Delaware) [7], for example, the design variables included the sizes and the timing of reservoir construction, target levels of power output, target levels of reservoir storage for recreation, target M & I and water supplies, allocation of flood storage and desired low-flow controls, etc. Random samples were taken of the individual variables in sequence in order to generate a set of alternative designs; minor adjustments were then made to each of these sample designs in search of the "best" design for the system as a whole. In the application to the six-reservoir system of the Lehigh River, this approach proved quite successful.

In the case of the overall Delaware Basin simulation, which has many more design alternatives, the sampling approach appears far too time consuming and expensive. Indeed, the system offers so many choice variables that it becomes difficult to find a basis in engineering judgment for a set of trial designs; and even given a trial design it is difficult to formulate marginal changes which improve the overall economic performance.

Mathematical Models for Preliminary Screening

In an attempt to find ways to simplify this task we took up the study of simpler, faster and more flexible basin-wide

models which--although less accurate than the simulation approach--could be used to screen out a large proportion of the possible designs as economically inferior and to gain a rough indication of which system configurations might turn out to be the more attractive. In the pursuance of this work, we were fortunate to have the cooperation of Daniel P. Loucks of Cornell University. During the spring and summer of 1968 he was associated with the Water Resources Group in the Division of Engineering and Applied Physics at Harvard--his primary effort being devoted to the study of mathematical programming models of water resource systems. His work with the Division proved to have a productive application in connection with our problem of preliminary screening; discussion of the structure of the mathematical models tailored to this application is provided in a paper by Loucks, "Preliminary Screening Models for River Basin Planning" [8].

In approaching the study of preliminary screening models for use in combination with digital simulation, it was decided to start not with the overall Delaware Basin but with a smaller and more tractable system; and the first efforts were devoted to screening-simulation studies of the Schuylkill River Basin. This is a five-reservoir system involving municipal water supply, recreation, flow augmentation, and a potential for power production. A series of different types of mathematical programming models was developed for this system, and the Delaware Basin simulation was revised to allow consideration of the Schuylkill as a separate entity. The simulation program was run in concert with the screening models in order to check their performance in representing system characteristics and to investigate alternative ways of using the information produced by the mathematical programming models.

The results of this work have been encouraging: experience to date indicates that these preliminary screening models can be set up and solved with a reasonable input of time and expense, and that they can be a great help in identifying those system plans that are worth studying in detail by digital simulation.

Systems Models for Evaluation of Flow Augmentation

The larger the flow in a river or stream the more waste material it can absorb without serious ecological change and consequent loss in recreational and aesthetic value. Because this is so, acute water pollution problems occur most often during periods of low streamflow, and the requirements of the low-flow period usually are a controlling factor in the design of waste management systems. Low-flow conditions can be improved at a cost, of course, and in some cases

investment in flow regulation may be an effective and efficient component of quality control policy. The purpose of research in this area has been to develop analytical models that describe the effects of flow regulation, and that can be used to evaluate the relative attractiveness of reservoir storage when used in concert with other quality control instruments.

The analysis of flow regulation schemes turns out to be a rather complex task, for several reasons. Consideration must be given to stream hydrology, to reservoir construction, and to the combination of storage system design and operation that will achieve specified degrees of flow regulation. The evaluation is made more complicated by the fact that regulating reservoirs often serve multiple purposes, such as recreation, water supply, flood control, or power generation. And, to add to these difficulties, careful analysis is required to define the interaction between streamflow control and waste treatment as they affect water quality at different points downstream.

As mentioned in the previous section, the analysis of multipurpose reservoir systems can be a complicated and expensive matter. Often, the analysis is based upon digital simulation, and to get the most out of expenditure on these simulation studies there is need for a procedure that can be used to screen large numbers of possible flow regulation schemes and pick out the relatively small range of alternatives that merits more thorough investigation. Once again, it is toward this preliminary screening problem that the model development efforts have been directed.

Consideration of the Political Dimension

In eliminating or "screening out" the less attractive opportunities, consideration is taken of political as well as technical and economic factors. The term "preliminary screening" normally refers to the rapid, crude analysis of projects in search of a small number that are technically feasible and that appear to perform well under some established standard of evaluation or objective function. This research begins from a different viewpoint, and argues that the precise statement of relevant objectives that is required for mathematical analysis quite often is not available, particularly in the early stages of project evaluation. At best, objectives are worked out as the project develops, and in many instances the purposes for which a project is undertaken, and the influences that shape its design, may never be formulated explicitly. This occurs because, in a public decision such as quality control by flow augmentation, there will be several groups--Federal and local, private and public--whose

interests in the outcome may diverge, and yet who carry significant weight in the ultimate choice.

In this circumstance, any preliminary screening process, if it is to be useful, must incorporate an extra consideration besides pure technical and economic feasibility; it must have an eye to the potential for political survival of alternative proposals. It does little good to identify projects that look attractive in the light of the objectives of some particular group, but that will never get beyond the drawing board because of factors the analysis did not incorporate. The successful analyst carries these considerations in the back of his head, of course, and tries to take them into account when and where appropriate. By building our analysis on the conceptual framework laid down in the work on political factors summarized above, however, it becomes possible to make explicit provision for the political dimension of the screening task.

Mathematical Models for Basin Analysis

Much of the development and testing of flow augmentation models has been carried out using a case example. For this purpose, the hypothetical river basin utilized by Dorfman and Jacoby [3,5] serves well, particularly since use is made of the model of political decision which that basin was designed to elaborate. Most of the descriptive information developed for the former study is carried over for use in the analysis of flow regulation. Of course, the basin has been expanded to include flow regulation as an alternative quality control instrument.

Several mathematical models are used in the overall analysis. One set of models is designed to analyze multipurpose reservoir projects. A reservoir release rule has been developed that is compatibele with the low-flow conditions specified in most water quality standards, yet is suitable for inclusion in analytical models. Applying this release procedure, a mathematical model of a multipurpose reservoir system has been formulated, using recreation and flow regulation as companion purposes for the storage facilities. Because reservoir pool elevation affects recreation activity, the model has been designed to permit consideration of fluctuations in storage that are imposed by operation for flow control. Of course, recreation is only one of many reservoir uses that is affected by variation in water level; it does, however, serve as a convenient example.

The results of this analysis of regulation devices have been combined into an overall study of basin-wide water quality management policy, and here use is made of a mathematical model of biochemical quality in natural streams. Based on solutions

to this set of models, it proves possible to screen out large regions of possible system designs and focus attention on a relatively small set of alternatives that appears to merit further study.

The results of this research are reported in an essay by Daniel P. Loucks and Henry D. Jacoby [9].

Research on the Use of Regional Analysis in Water Resource Planning

Regional Analysis of Quality Control Costs

In the original formulation of this research project, a collaborative effort was envisioned whereby we would work alongside individuals in the Department of Regional Science of the University of Pennsylvania and the Regional Science Research Institute in an attempt to integrate methods of regional economic analysis with studies of the economics of water supply and quality. The primary emphasis of the work of the regional science group has been on the potential use of regional input-output techniques to estimate future demands for water supply and water disposal in the region of the Delaware Estuary and to devise methods for forecasting the spatial distribution of waste loads along the estuary. We have maintained close working contact with their efforts over the grant period.

In addition to our work in cooperation with the regional science group, we have undertaken our own study of the application of regional input-output methods to water quality problems. A paper by William E. Martin, "The Use and Value of Input-Output Models in the Analysis of Water Pollution Abatement" [11] explores potential applications of this technique. The paper begins with a brief description of the basic components of input-output models and of the way in which such models may be extended to include data related to the use of primary resources. The discussion focuses on data relative to water quantities and qualities. A second section presents a general discussion of the possible value of input-output analysis of problems of pollution abatement, and the final section develops an empirical example of one possible use.

The case example, once again, is the Delaware Estuary, and an input-output model is used to estimate the relative sizes of abatement costs--and on whom they would fall--if pollution were controlled by treatment plants, or alternatively, by restrictions on industrial output. Although designed primarily as an example of the way in which regional analysis might be applied to pollution problems, the study also concludes that, in the Delaware case, treatment costs are

relatively small compared to the direct and indirect effects on the output of industries such as petroleum, chemicals and paper, which are large contributors to the regional waste load.

A Model of the Interdependence between a Regional Economy and Water Quality Control Efforts

A second, similar research effort has been devoted to the preparation of a model that describes the interdependence of a regional economy and a river flowing through it. What is desired is a model that can be used to measure the effect of regional growth (and associated locational changes) on a river's reaches and to assess the influence of alternative regional waste management policies. And this orientation leads to a concern with the way expenditures in the water supply and sewage treatment sectors tend to feed back into the regional economy--resulting in increased levels of output and employment and, unfortunately, increased levels of pollution generated by the region's industries. The analysis of these phenomena rests on a static regional input-output model that has been expanded to include consideration of the river, and of the geographical distribution of waste generating activities.

Under this mode of analysis, all water users and waste sources in a region are considered. The usual distinctions are made between intermediate industries, households, and government of all levels operating in the region. And, for purposes of analyzing water supply and quality, these entities are further classified into three groups of water users. The first group consists of units that rely on water supply and sewer services for their intake and discharge of the river's water. The second includes those who do not use public water and sewer services, but are directly linked to the river by withdrawing water and subsequently discharging it after some level of treatment. The third group contains water users who either (a) do not use the river's water, but rely on groundwater sources and then discharge into the river, or (b) are located in another drainage basin and use the water supply and waste disposal services of some other river.

The key linkage between these diverse elements of the river and the regional economy, then, is provided by the water supply and sewer services that transport water and alter its quality through various treatment processes. There are well-defined areas within a metropolitan region that are linked to the river at specific points of water intake and sewer outfall. And, therefore, in order to measure the locational incidence of wastewater discharge, the spatial distribution of water users, as they are tied to different reaches of the river, must be specified.

In conventional input-output analysis, however, no information is available regarding activity levels by subarea, or about flows of goods and services among subareas of a region. Consequently, to carry forward this regional analysis it is necessary to partition the metropolitan region into local areas corresponding to water supply and sewer service systems. The development of techniques for spatial disaggregation of water utilization coefficients (intake, discharge, wasteload) has been one of the major components of this research effort.

Once the model has been formulated, it becomes possible to simulate the growth of a metropolitan region over time and to assess the impact of the regional economy on the river under alternate policies regarding level of waste treatment, flow regulation, regionalized treatment, etc. The spatial dimension of the growth of wasteloads thus may be considered in the analysis of alternate management schemes, and it becomes possible to evaluate the significance of alternative control schemes on the regional economy itself.

Preliminary results of this research are reported in a paper by Eliahu Romanoff, "The Interdependence of a Regional Economy and a River" [13]. Work on this topic has not been completed, however.

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SECTION III

A MONOGRAPH ON WATER QUALITY MANAGEMENT

As mentioned at the outset, one of the purposes of Grant No. 16090 DTF has been to make possible the integration of individual research efforts, along with the output of other water quality investigations at Harvard, into a cohesive monograph. An important goal of our research in water resources over the years has been to bring together the knowledge of several disciplines--physical and biological science, engineering, economics, and political science--and to develop a coordinated approach to water resource management. Twice in the past, water research at Harvard has been drawn together in this fashion--first in the book Design of Water-Resource Systems by Maass, et al. [10]., and later in the monograph on Simulation Techniques for River Basin Planning, by Hufschmidt and Fiering [7]. The preparation of these volumes not only provided a healthy exercise for the researchers and authors themselves--for it forced them to bring their several disciplines to bear on common problems--but it also made research results available to a wider audience of water resource managers, analysts, and researchers than would otherwise have been possible.

The latest monograph is a collection of nine essays selected from recent research at Harvard. The book has been titled Models for Managing Regional Water Quality.

The first essay, by Harold A. Thomas, Jr., provides a broad perspective of the water pollution problem in an historical setting. It reviews the antecedents of current practice in water quality control and lays the groundwork of ecological principles and engineering knowledge upon which the analyses in subsequent chapters are built. Special attention is given to the problem of biochemical pollution from human and industrial wastes, and to the empirical basis of the mathematical models commonly used to describe this phenomenon.

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The next three chapters present research (conducted under this grant) by Robert Dorfman, Henry D. Jacoby, and Clifford S. Russell. These chapters endeavor to integrate social and economic considerations with the technological and engineering aspects of water quality management. Chapter 2 by Robert Dorfman, "Conceptual Model of a Regional Water Quality Authority" [2], introduces the political model described earlier and advocates its application to the analysis of pollution control institutions and projects. In Chapter 3, "An Illustrative Model of River Basin Pollution Control" [3], Robert Dorfman and Henry D. Jacoby present the results of the preliminary test of the model, using the hypothetical river basin. And in Chapter 4, "Municipal Evaluation of Regional Water Quality Management Proposals" [14], the results of the Russell study discussed above are detailed.

Chapters 5 and 6 present the work by Stephen J. Turnovsky. The first of these chapters, "Microeconomic Behavior When Supplies Are Uncertain" [25], explores the behavior of micro-economic units--consuming households and productive firms--when the supply of some input is subject to uncertainty. Applying and extending these results, a second chapter, "Optimum Government Investment in Supply Systems Yielding Uncertain Outputs" [26], considers the optimal planning of public investment and management schemes when there is a stochastic component in the pattern of goods they provide. Particular attention is devoted to the estimation of benefit functions in this situation, and to the design of supply systems when output variance is subject to control.

The last three chapters in the book investigate some of the different combinations of control instruments that may be applied to particular regional water quality problems. Waste reduction at the source is the most common method of pollution abatement, but there are others. For example, it is possible to apply remedial measures to the water body itself, through the use of flow augmentation, artificial aeration, or the removal of blankets of sludge or coatings of oil. Alternatively, wastes can be collected from diverse sources and treated in a central facility, or they can be piped out of the region altogether.

Generally, the efficient use of such measures requires close coordination with plans for waste treatment by individual dischargers, for they can change the magnitude and geographical distribution of the assimilative capacity of the receiving waters, or of the waste loads themselves. Study of these alternatives, therefore, is best carried out in the context of systems models that can encompass a complicated interdependence among the choices that are open. Each of the last three studies is a quest for new capacity to perform this type of analysis.

Chapter 7 by Leonard Ortolano, "Artificial Aeration as a Substitute for Wastewater Treatment" [12], is concerned with the use of artificial aerators for control of dissolved oxygen in estuaries. In a sample problem, which incorporates data from the Delaware Estuary, a study is made of the choice between the introduction of mechanical aerators and the installation of advanced waste treatment. Several aspects of such a system render this a challenging analytical problem. The relationship between aerator performance and ambient stream conditions is a complicated one: the lower the dissolved oxygen level, the greater the rate of aeration from an artificial device. Furthermore, aerators can be installed at any point in an estuary, and they can be easily removed or shifted to other locations as conditions change. Advanced waste treatment facilities, on the other hand, are fixed in place, but they are subject to economies of scale in plant size. Capacity tends to be built ahead of demand, as a result, and the planning analysis must cover multiple time periods. These characteristics contribute computational difficulties, and the bulk of the paper is devoted to the development of mathematical programming formulations and computer algorithms to deal with them.

Chapter 8 by Tze-wen Chi, "Wastewater Conveyance Models," [1], considers wastewater conveyance and regional treatment facilities. The analysis is similar to that applied to aeration. The sample problem is concerned with multiperiod planning of estuarine quality control, once again using data from the Delaware. In this chapter, however, the alternative to on-site waste removal is to transport wastes to some combination of regional treatment plants, or to pipe them out of the region.

Not surprisingly, the consideration of pipe design introduces special analytical difficulties of its own. There are economies of scale in pipe construction; and the relationships among pipe diameter, flow rate, pump design, and energy cost, though well understood, are complicated. In addition, it can prove efficient to install a trunk sewer that flows one way in one time period and in the reverse direction the next. Thus the analysis must consider pipe capacity, flow rate and direction, as well as the complexities of treatment plant design and operation. As in the preceding chapter, much of the discussion is directed to mathematical and computational procedures adequate to the problem.

Both the Ortolano and Chi studies were carried out under the sponsorship of FWQA grants other than the one being reported upon here. They were assisted by grants on "Operations Research in Water Quality Management" (Grant No. WP-00111) and "Dynamic Planning Techniques for Pollution Abatement" (Grant No. 16090 DSS).

The chapters on aeration and wastewater conveyance give full attention to the solution of analytical problems inherent in the economic and technical characteristics of those control measures. They do not emphasize the institutional orientation of the early chapters. Chapter 9 on "Flow Regulation for Water Quality Management" [9], by Daniel P. Loucks and Henry D. Jacoby, reports on the study of flow augmentation that was described earlier, and this last essay does integrate the technical work on quality models and the institutional concerns of the early chapters.

That completes the book. As this brief summary indicates, most of the work is exploratory. Furthermore, the emphasis throughout is on the development of analytical models that can encompass the technical and social facets of a complicated subject, and the coverage is necessarily spotty. There is much discussion of biochemical pollution but scant attention to other critical problems such as waste heat, radioactive discharge, inorganic industrial chemicals, and agricultural runoff. There is a good deal of work on models suited to rivers and estuaries; little effort is devoted to lakes, bays, and coastal areas. Municipalities are subjected to close scrutiny; independent industrial dischargers are handled in summary fashion.

Thus, in a sense, these studies comprise less a book about water quality than one about methods for analyzing problems of water quality. The research has been less comprehensive in considering all instances of water pollution and more integrative in attempting to tie together the physical, economic, and institutional aspects of regional management. Our hope is that these essays can provide a stepping-stone to further research and to improved analysis for the hard, practical task of environmental protection.

SECTION IV

ACKNOWLEDGMENTS

Thanks are due to many people for their efforts in support of this work over the past several years. The papers presented here are drawn from recent research by participants in the Harvard Water Program: these studies represent the latest stage in a fifteen-year history of inter-disciplinary research in water resources under the Program's auspices.

Since its inception, the Water Program has been organized within Harvard's John F. Kennedy School of Government, and it has worked hand-in-glove with the water resources group in the Division of Engineering and Applied Physics. The research activity has enjoyed strong support as well from the Department of Economics. It is difficult to imagine better circumstances for this type of cooperative effort, and our debt to the leadership of these departments is great.

The primary vehicle for organizing and sustaining the research effort has been a graduate seminar sponsored jointly by the Economics Department and the Kennedy School. From semester to semester its function has been the same, i.e., to provide a forum for the presentation of ideas and preliminary drafts, and an opportunity to receive criticism and suggestions. Each of the nine chapters was presented to the seminar at one stage or another: most were worked over more than once on the long path from initial conception to completed papers.

What this means, of course, is that a good deal of hard work, and often some very important suggestions, were contributed by persons who are not listed here. Every year the seminar enjoys the active participation of several Harvard faculty members, and of students from both Harvard and MIT. There are too many to credit them all. There are several whose omission would be a gross injustice, however, and we are happy

to give special thanks to Robert Burden, Russell deLucia, Joseph Harrington, Daniel Leucke, Arthur Maass, Peter Rogers, Grant W. Schaumburg, Jr., and Richard Woodward.

Finally, much of this research might never havebeen undertaken without continuing support, both financial and personal, from Resources for the Future, Inc.

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27 Abstract

Research has been directed to a series of problems in water resource management. One pair of projects has focused on problems of water supply planning under uncertainty, and improved methods of analysis for planning have been developed.

A set of four research efforts has been devoted to problems of water quality management, with special attention given to the decisions faced by municipalities and regional authorities. New conceptual models of quality management institutions have been proposed, and the conceptual framework has been applied to several sample river basins.

A third focus has been on the development of improved computing methods for analysis of river basins. Two projects have contributed new analytical models for preliminary screening of river basin designs. Special attention has been directed to the analysis of flow augmentation for water quality management.

Finally, research has been carried out on the use of regional analysis in water resource planning. A static regional input-output model has also been developed that can analyze the interrelations between regional growth and efforts at water quality control.

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